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The Atmospheric Infrared Sounder (AIRS) on the Earth Observing System: In-orbit Radiometric and Spectral Calibration

M. }1. Aumann
Jct Propulsion Laboratory
Pasadena, CA 91109, USA

Ken Overoye
LORAL Infrared & Imaging Systems
Lexington, MA 02173, USA

ABSTRACT

The Atmospheric Infrared Sounder (AIRS) is a high spectral resolution IR spectrometer. AIRS, together with the Advanced Microwave Sounding Unit (AMSU) and the Microwave Humidity Sounder (MHS), is designed to meet the operational weather prediction requirements of the National Oceanic and Atmospheric Administration (NOAA) and the global change research objectives of the National Aeronautics and Space Administration (NASA). The three instruments will be launched in the year 2000 on the EOS-PM 1 spacecraft. Testing of the AIRS engineering model will start in 1996.

The AIRS instrument represents a major step forward in satellite based remote sensing technology. In particular, improvements in second generation PV:HgCdTe detector array/readout technology coupled with a rapid advance in long life, low vibration, Stirling/pulse tube cryocooler design have been instrumental. This paper focuses on inflight radiometric and spectral calibration of AIRS.

Keywords: EOS, AIRS, infrared, sounder, echelle grating, HgCdTe detector, Stirling cycle cryocooler, calibration

1. INTRODUCTION

The HIRS (High Resolution Infrared Sounder) and the Microwave Sounding Unit (MSU) on the National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellite system have supported the National Weather Service (NWS) weather forecasting effort with global temperature and moisture soundings since the late 70's. After analyzing the impact of the first ten years of HIRS/MSU data on weather forecast accuracy, the World Meteorological Organization in 1987 (Ref. 1) determined that global temperature and moisture soundings with radiosonde accuracy arc required to significantly improved the weather forecast. Radiosonde accuracy is equivalent to profiles with 1K rms accuracy in 1 km thick layers and humidity profiles with a 20% accuracy in the troposphere. This requirements was far beyond the capability of the HIRS sensor technology. Breakthroughs in IR detector array and cryogenic cooler technology by 19S7 made this requirement realizable wit h technology available for launch at the end of this century. AIRS is the product of this new technology. AIRS, working together with the Advanced Microwave Sounding Unit (AMSU) and the Microwave Humidity Sounder (MHS), forms a complementary sounding system for NASA's Earth Observing System (EOS) to be launched in the year 2000. The three instruments arc expected to become the operational sounding system for the National Polar-Orbiting Operational Environmental Satellite System (NPOESS) to be launched early next century.

The measurement concept employed by AIRS/AMSU/MHS follows the concept originally proposed by Kaplan (Ref.2) in 1959, verified experimentally ten years later using the Satellite Infrared Radiation Spectrometer (SIRS) and used operationally by the HIRS/MSU. Temperature and moisture profiles arc measured by observing the upwelling radiance in the Carbon dioxide bands at 4,2 μm and 15 pm, and the water band at 6.3 μm. However, compared to the HIRS spectral resolution of about 50, the AIRS will have a spectral resolution of 1200. The high spectral resolution gives sharp weighting functions and minimizes the contamination of temperature sounding channels with water lines, other atmospheric gases or surface emission. Correction for spectral Earth surface emissivity and reflectivity effects can be obtained by observing selected surface channels distributed throughout the 3.8 μm -13 μm region. Accurate retrievals under partly cloudy conditions arc obtained by combining the infrared measurements with collocated microwave data from the AMSU (27-89 GHz) and the MHS (89-183 GHz).

The AIRS instrument represents a major step forward in satellite based generation PV:HgCdTe detector array/readout technology coupled with a rapid advance in long life, low vibration, Stiriing/pulse tube cryocooler design have been instrumental. The AIRS hardware development phase has been underway since 1991, and considerable progress has been made since that time. The Preliminary Design Review (PDR) for AIRS was held in January 1995. A test facility especially design for AIRS will be used to accomplish a complete pre-launch spectral, spatial and radiometric calibration of AIRS. Testing of the Engineering Model, starting in mid 1996 is expected to be complete in Summer 1997. The delivery of a Protoflight Model is expected in September 1998. AIRS is designed for an operating lifetime of 5 years, with hardware redundancy in all critical subsystems. The AIRS power, size and weight requirement, 256 watts and 156 kg, is comparable to other instruments of this class and is easily accommodated on the EOS-PM 1 satellite. Wc have previously (Ref.3) described the AIRS hardware. The present paper briefly reviews the AIRS measurement requirements and instrument description, but focuses on inflight radiometric and spectral calibration.

2.0 AIRS MEASUREMENT REQUIREMENTS AND INSTRUMENT SPECIFICATIONS

The Interagency Temperature Sounder (ITS) Team, with representatives from NASA, NOAA and DOD, was formed in 1987 to convert the NOAA requirement for radiosonde accuracy retrievals to measurement requirements of an operational sounder. An extensive effort of data simulation and retrieval algorithm development was required to establish instrument measurement requirements in the areas of spectral coverage, resolution, calibration, and stability, spatial response characteristics including alignment, uniformity, and measurement simultaneity, radiometric and photometric calibration and sensitivity. Sensitivity is expressed as Noise Equivalent Delta Temperature, NEAT, referred to a 250K target temperature. The Functional Requirements Document (FRD) (Ref. 4) has been under formal change control since 1992.

3.0 AIRS SYSTEM DESCRIPTION

The AIRS Instrument, shown in Figure 1, provides spectral coverage in the 3,74-4.61 pm, 6.20-8.22 pm, and 8.8-15.4 μm infrared wavebands at a nominal spectral resolution $\lambda/\Delta\lambda$ = 1200, with 2378 spectral samples. Kcy to the spatial coverage and the calibration is the scan head assembly, containing the scan mirror and the calibrators (arrows in Figure 1.) . An exploded view of the scan head assembly is shown in Figure 2, A 360 degree rotation of the scan mirror generates a scan line of IR data every 2.667 seconds. The scan mirror motor has two speeds: During the first 2 seconds it rotates at 49.5 degrees/second, generating a scan line with 90 ground footprints, each with a 1.1 degree diameter IFOV. During the remaining 0.667 seconds the scan mirror completes one complete revolut ion with four independent views of cold space, onc view into a 3 10K radiometric calibrator, one view into a 330K spectral reference source, and one view into a photometric calibrator. The VIS/NIR photometer, with a 0.185 degree IFOV, is boresighted to the IR spectrometer to allow simultaneous visible and infrared scene measurements.

The diffraction grating in the JR spectrometer disperses the radiation onto 17 linear arrays of HgCdTe detectors (Figure 3.) in grating orders 3 through 11. The IR spectrometer is cooled to 150K by a two stage radiative cooler. The IR focal plane is cooled to 60K by a Stirling/pulse tube cryocooler. The scan mirror is cooled to 273K by radiative coupling to the Earth and space scenes and to the 150K IR spectrometer. Cooling of the IR optics and detectors is necessary to achieve the required instrument sensitivity. The VIS/NIR photometer uses optical filters to define four spectral bands in the 400 nm to 1000 nm region. The VIS/NI R detectors arc not cooled and operate in the 293K to 300K ambient range of the inst rument housing.

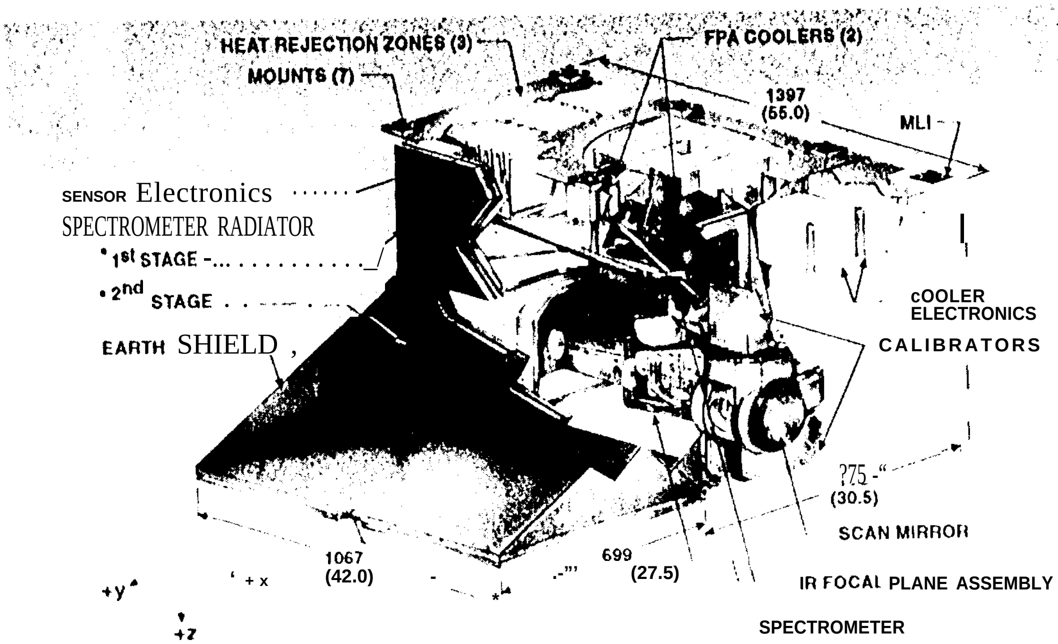

Figure 1. The AIRS instrument illustration shows key hardware elements. The thermal blanket is partly removed to show interior details. The spectrometer is small compared to the volume required to support the space radiators, cooler and electronics.

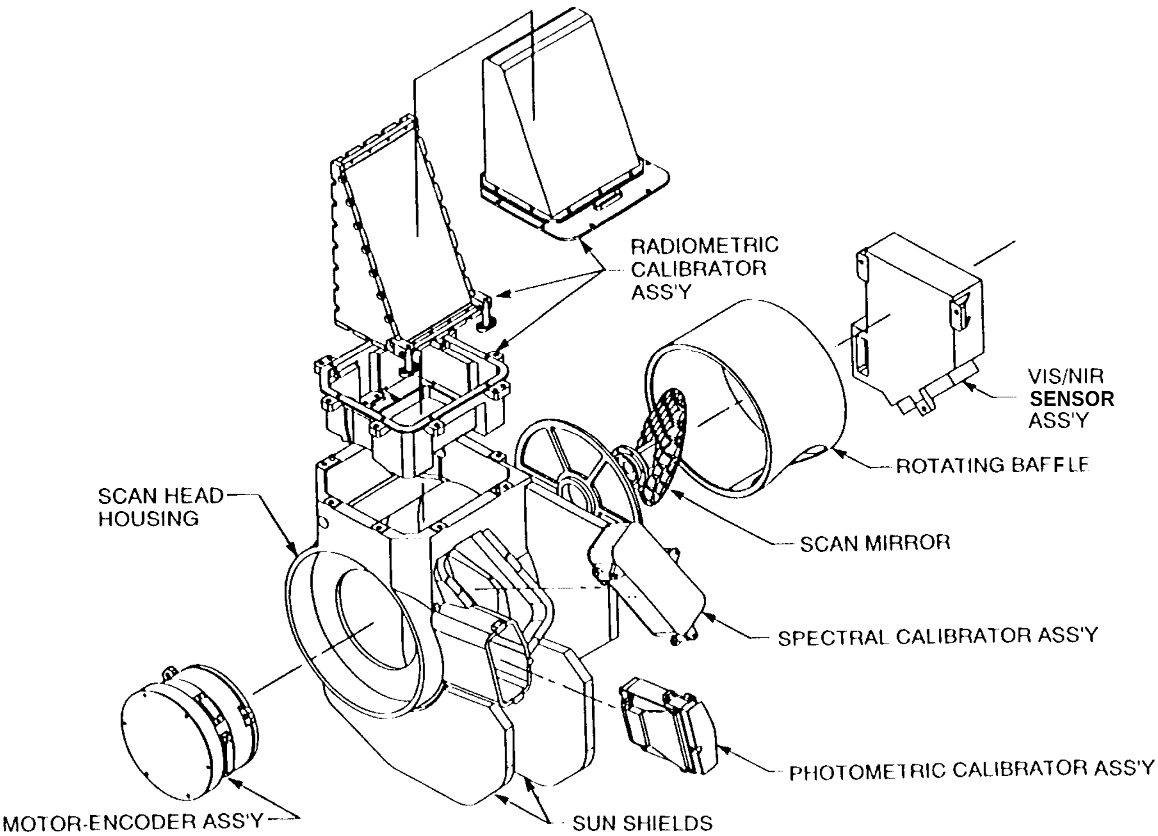

Figure 2. Exploded view of the AIRS scan head assembly. The scan mirror provides the cross-track spatial coverage, and generates a radiometric, photometricand space-view calibration every 2.67 seconds.

Signals from both the IR spectrometer and the VIS/NIR photometer arc passed through onboard signal and data processing electronics, which perform functions of radiation circumvention, gain and offset correction, signal integration, and output formatting and buffering to the high rate sciencc data bus. In addition, the AIRS Instrument contains command and control electronics whose functions include communications with the satellite platform, instrument redundancy reconfiguration, the generation of timing and control signals necessary for instrument operation, and collection of instrument engineering and housekeeping data. The Stirling/pulse tube cryocoolers arc driven by separate electronics which control the phase and amplitude of the compressor moving elements to minimize vibration. Heat from the electronics is removed through coldplates connected to the spacecraft's heat rejection systcm.

4. In-flight Radiometric Calibration, 3.7- 15.4µm.

The AIRS FRD calls for an absolute radiometric calibration accuracy of 3% of the signal or 50/(Signal-to-Noise-Ratio) in percent, whichever is larger, over the full range of expected effective target brightness temperatures, 220K -350K, and the full wavelength range covered by AIRS, during five years in orbit. This requirement requires careful considerations of many components which effect the radiometric calibration, There arc many issues which can contribute to a radiometric calibration error. Many potential sources of have been minimized in the AIRS design by conservative design, such as using over-sizs baffles or by lowering the temperature of critical elements, design changes, such as adding temperature probes in certain surfaces to allow for first order corrections in the calibration software or by expanding the preflight characterization. Figure 4 shows the contribution of the five most important contributors to the radiometric calibration error. The root mean square of all error is less than four times the noise-equivalent radiance (NEN).

4.1. The effect of residual non-linearities arc the largest contributor to the radiometric error. The AIRS detector electronics response to a linear signal amplitude sweep covering the 220K to 340K brightness temperature dynamic range during ground calibration will be fitted to a suitable polynomial to remove the effects of non-linearities. However, changes in the electronics duc to aging and/or prolonged exposure to ionizing particle radiation may produce deviations from the ground-calibration. The AIRS design includes provision for a potential in-orbit re-calibration of the photovoltaic detector (3.7- 13.4 µm range) signal change linearity. This is accomplished conceptually with a special calibration sequence, where the integration time is changed in 1 ms steps from lms to about 40 ms (the normal dwell time is 22 ins). If this concept can be validated during ground-calibration, non-linearity is an issue only for the 13.4- 15.4µm region.

4.2. Zero Point Offset Error varies in importance depending on the wavelength, but is second in importance to non-linearity for the 13.4 -15.4 µm region. The signal measured by AIRS viewing a ground target is the combination of the target radiance and the thermal emission from the AIRS instrument. Although the AIRS spectrometer is cooled to 150K and the detector wavelength response is limited to 5°A of the wavelength by cold interference filters, emission from the instrument exceeds the signal from a typical target at all but the shortest wavelengths. Radiance from the instrument is of the order of a factor of 50 larger than the target radiance at the longest wavelengths. Viewing cold space makes it possible to separate self-emission from target radiance. AIRS takes four space view measurements. The space views occur while the AIRS boresight vector is between 68.6 and 112.2 degree from nadir. These measurements arc followed by a view of the blackbody and a spectral reference source. The cycle repeats every 2.67 seconds. The space view is identical to the zeropoint only at the moment when the spaceview occurs. Between spaceviews drift in the electronics, including residual l/f noise induce an error. The AIRS is designed to keep this fluctuation to below onc NEN. in order to suppress the noise in individual space views, space views in a sliding window of about 5 minutes length will be fitted with a smoothing splint.

4.3. Gain/Offset coupled scan angle dependent effects exceed offset related error in the 9- 11µm region. The reason for this is the scan mirror coating. The Al RS scan mirror is made of beryllium, coated with silver, overcoated with a protective layer of SiOx in a proprietary process , FSS99 by Denton Vacuum Inc. This coating has very high reflectivity, excellent cleanability properties, and a proven durability record for prolonged space application. However, the overcoating produces a small of polarization in the 8- 12 µm region. Figure 5. shows a tracing of the spectral reflectivity for s- and p-wave polarization between 7.5 and 15.5pm relative to the reflectivity of pure gold. The effect is the strongest at 8.8 µm, where the s-wave reflectivity is 98%, but the p-wave reflectivity is only 86%. The polarization vector rotates with the rotation of the

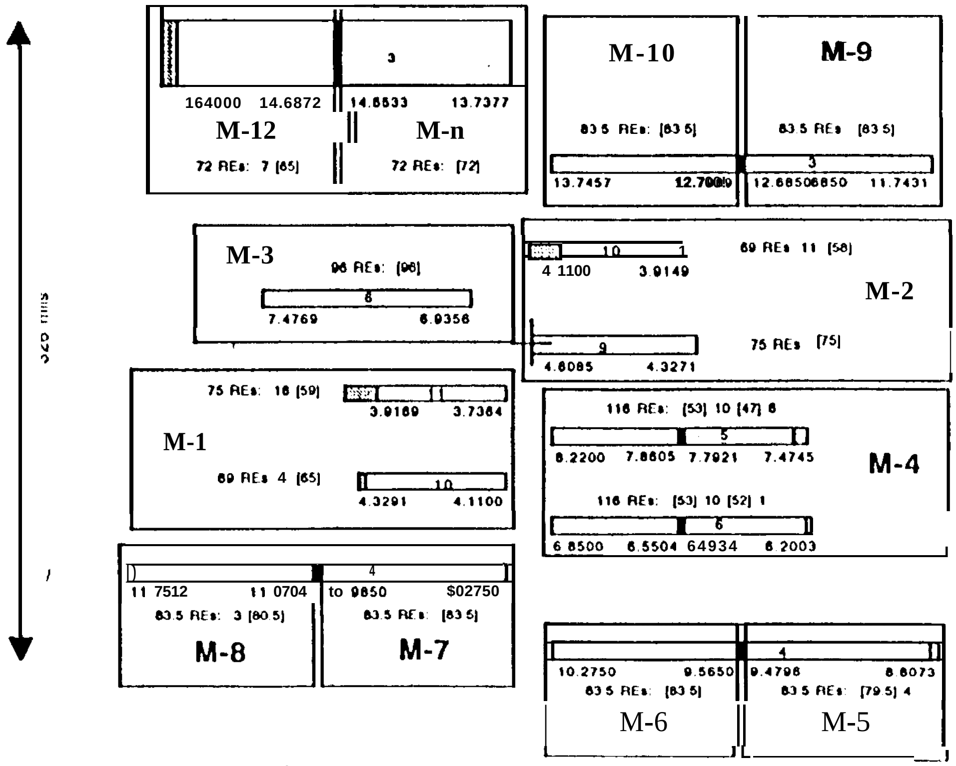

Figure 3. Each of eleven entrance apertures of the grating spectrometer is imaged onto a linear array in the focal plane. All arrays and associated readout electronics are mounted on a single ceramic substrate. This greatly simplifies the spectral calibration.

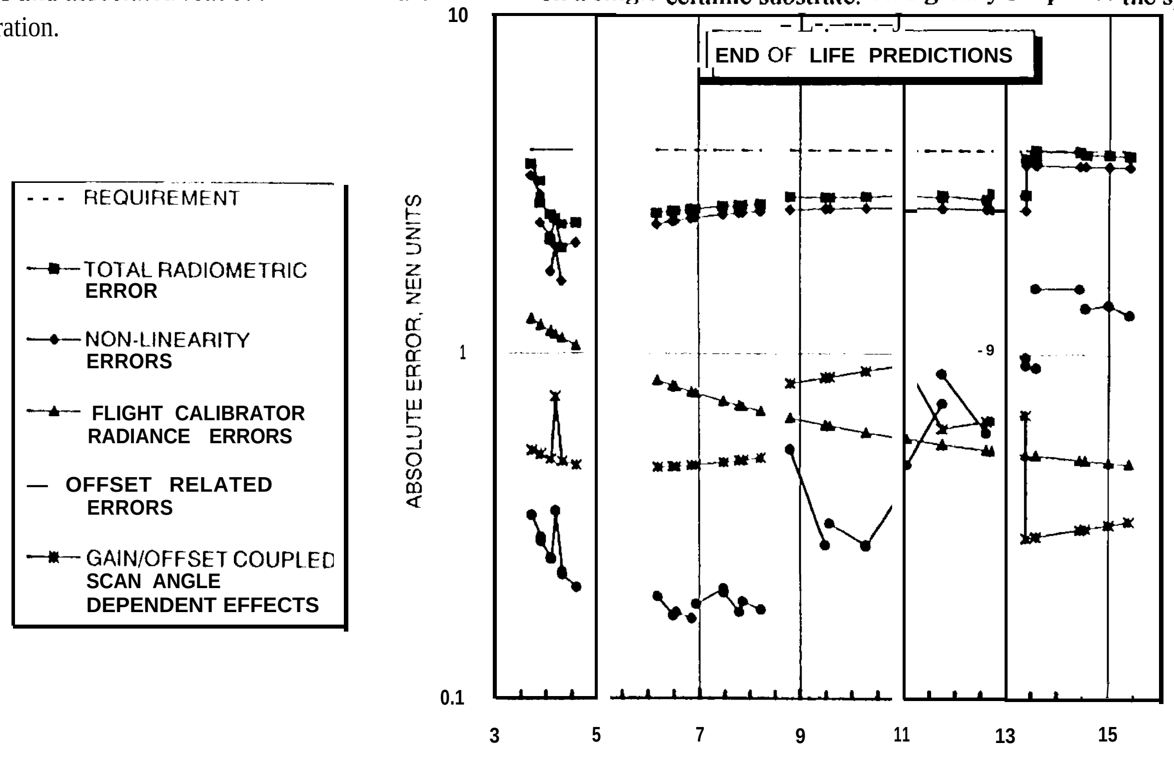

Figure 4. The predicted contribution of the four most significant contributors to radiometric calibration uncertainty. Estimates refer to worst case, end-of- life conditions. Under all conditions the uncertainty is less than four NEN units.

scan mirror. Thermal emission from the atmosphere is not polarized. Since the AIRS instrument transmission is polarization dependent, the combination of the rotating scan mirror and the instrument creates a polarizer/analyzer effect. In the following wc analyze the magnitude of this effect and show that it can be reduced to a negligible amount using first order correction terms obtained from ground calibration.

Let the scan mirror reflectance be rp and rs for the p- and s-polarizations. For an unpolarized incident flux, the polarization int reduced in the flux on reflection from the scan mirror is $p_r=|(rs-rp)/(rs+rp)|$. If tp and ts arc the transmission parallel and perpendicular, respectively, to the plane of maximum polarization, define $p_t=|(tp-ts)/(tp+ts)|$. The plane of maximum polarization makes an angle α relative to the spectrometer x-y plane. The radiance emitted by the AIRS calibration source, N., is measured at mirror position $\delta=\pi$ and the space observation occur near $\delta=\pi/2$. The modulation of the unpolarized incident flux N is then given by

$$dN = p_r\, p_t\ (\ N(\cos 2(\delta-\alpha) - (1-2L/N_c)\cos 2\alpha - 1.(\cos 2(\delta-\alpha) + \cos 2\alpha)),$$

where L is the black body function of the scan mirror and δ is the rotation angle of the scan mirror about the x-axis. If the scan mirror temperature is 273K and α=22.5 degree, p_t=0. 15 and p_r=0.03, then dN equals about three times larger than the nominal rms noise equivalent radiance, NEN, in the 9-11 μm region, We assume that the effect can be reduced by a factor of four to less than onc NEN in the 9-11 μm region with a first order correction based on the knowledge of the scan mirror reflective properties and the knowledge of the scan mirror temperature. The scan mirror temperature is measured in flight by a non-contacting temperature sensor built into the rotating axis of the scan mirror mounting assembly.

4.4. The on-board calibrator is the most obvious source of potential calibration error, but, as it turns out, the estimated error is second to non-linearity error only at the shorter wavelengths. This is caused by the increasing non-linearity of the black-body curve at the shorter wavelengths, which makes the knowledge of the temperature of the radiating surfaces important. The radiometric calibrator, shown in Figure 2, is a deep wedge cavity blackbody design with a rectangular 5.7 cm by 9.5 cm clear aperture. The depth of the blackbody cavity is two times the diagonal of the clear aperture. The blackbody housing and cavity arc made from beryllium to reduce its mass to 2kg. The cavity walls arc painted to maintain an emissivity better 0.91. The end of life emissivity of no less than 0.993 is obtained through the multiple bounces of the light within the cavity. The deep cavity design and the multiple bounces make this design very insensitive to surface contamination during prolonged storage of the instrument on the ground or due to contamination in orbit. The blackbody is temperature controlled to 3 10K using tape heaters. Temperature uniformity of the radiating surfaces is expected to be 0.1 K. Four dual redundant temperature sensors monitor the temperature distribution over the cavity surface to an accuracy of 40 mK. The black-body is calibrated pre-flight relative to a NIST traceable secondary standard.

S. Spectral Calibration in the 3.4- 1S.4 pm range.

The AIRS FRD calls for knowledge of the wavelength of the centroid of each array clement to within 1% of the spectral bandwidth. In addition, the AIRS FRD limits the drift of the centroid location to $0.05*\Delta\lambda$ during any 24 hour period. The latter requirement limits calibration drift to a sufficiently small amount, that the spectrum can be shifted to nominal wavelengths set with an interpolation algorithm as part of the ground-data processing without introducing additional errors.

The spectral calibration concept of AIRS has undergone a change since the Preliminary Design Review (PDR) in January 1995. At the PDR the wavelength calibration assembly used a Fabry-Perot plate. mounted infrontofa310K source (Ref.3). With a plate separation of 350 microns, the transmission spectrum contains hundreds of transmission peaks within the wavelength range of AIRS. In addition to serving as the reference for the absolute spectral calibration, this assembly also supported ground testing outside of the calibration test chamber by providing a internal source of high spectral contrast. This approach was abandoned when it became clear that the Fabry-Perot plate was much more difficul t to fabricate than expected and that the stability of the plate separation could not be assured over the five year mission life. The initial reaction to this was to plan to periodically calibrate the F-abry-Perot spectrum in-orbit relative to the upwelling spectral radiance and to usc the Fabry-Perot plate as a spectral calibration transfer standard. After evaluating the Fabry-Perot plate calibration procedure using the upwelling spectral radiance, it became clear that the AIRS spectrometer design is self-calibrating and that a transfer standard was not needed. With some changes in the ground-calibration software, the absolute spectral calibration of the entire AIRS spectral range is possible using the upwelling radiance spectrum directly, A decision was therefore made to eliminate the Fabry-Perot plate. in order to maintain functionality for quick ground-testing, the Fabry-Perot plate was replaced by a mirror coated with a thin film (about 100 micron thick) of Parylene. In order to avoid potential delamination after prolonged space exposure, the Parylene is overcoated with a protective layer of HgCdTe. Parylene is commonly used for the conformal coating of circuit boards. The spectrum of Parylene contains many well defined spectral features which have found widespread application in commercial spectrometers for quick testing of functionality and calibration.

AIRS now achieves its absolute wavelength calibration by comparing the observed upwelling spectral radiance with the spectral radiance calculated based on the precise knowledge of the line centers and strengths of the active gases. The upwelling spectral radiance, which is observed on each detector in steps of $\Delta\lambda/2400$, is compared with the prediced spectral radiance, with is calculated with a factor 10 smaller step size, using a correlation algorithm. In principle, every AIRS spectrum could be used to check the wavelength calibration. In practice, four observations closest to nadir and under cloud-free conditions will be used for the routine monitoring of the spectral calibration. Recalibrations, if necessary, could be based on spectra gathered during five minute intervals, which contain more than hundred scan lines.

The AIRS spectral calibration is best discussed by starting with the grating equation

$$m * \lambda = d * (\sin a - \sin \eta),$$

where m is the grating order, λ is the wavelength, d is the spacing between grating rulings, α is the angle of incidence of light on the grating and η is the angle at which the diffracted light leaves the grat ing. In the case of AIRS, m ranges from 3 at the longest wavelengths to 11 at the shortest wavelengths. We can re-write this equation to express the wavelength of detector i, λ_i, in terms of its position Xi in the direction of dispersion relative an arbitrary reference line Xo in the focal plane.

$$\lambda_i = d/m\,(\sin a - \sin(\mathrm{atan}((Xo-X_i)/L))),$$

where L is the distance of the focal plane from the collimating mirror. During the alignment of the instrument prelaunch L is set equal to the focal length of the collimating mirror. L and Xo can be adjusted in-flight by turning three precision screws of the collimating mirror alignment assembly.

All detectors of an array are photoetched on a common HgCdTe wafer and all arrays and associated readout electronics are mounted on a single ceramic subst rate. The positions Xi of all detectors relative to Xo is measured when the focal plane is assembled and is verified during the spectral system calibration on the ground. Since the grating order m is selected for each array by order isolation filters, the wavelength calibration of the entire focal plane in flight thus depends on monitoring four parameters: d, α, Xo and L.

Changes in d, a, Xo and L, after the launch and gravity release effects, are all related to changes in the thermal environment in the orbit and the thermal time constant of the instrument. Thermal environment changes occur in the vicinity of the poles as the spacecraft enters or leaves the Earth's shadow ever 50 minutes. The response of the instrument to these changes is attenuated by the instrument thermal time constant, estimated to be about 20 hours. Changes in the spectral calibration will therefore occur very slowly compared to the spectral calibration monitoring. We expect that almost the entire change in the spectral calibration after the initial stabilization period will be in parameter Xo.

in the AIRS wavelength calibration algorithm concept, which is currently in the prototype phase, we select small wavelength regions, each about 20 detectors wide, for each of the 17 arrays, and use the upwelling spectral radiance to solve for d, a, Xo and L in a least-square sense. The accuracy of this solution is in principle limited by uncertainty in the knowledge of the temperature and moisture profile and the finite signal-to-noise of the detectors. in practice, better than the required accuracy should be easily achievable.

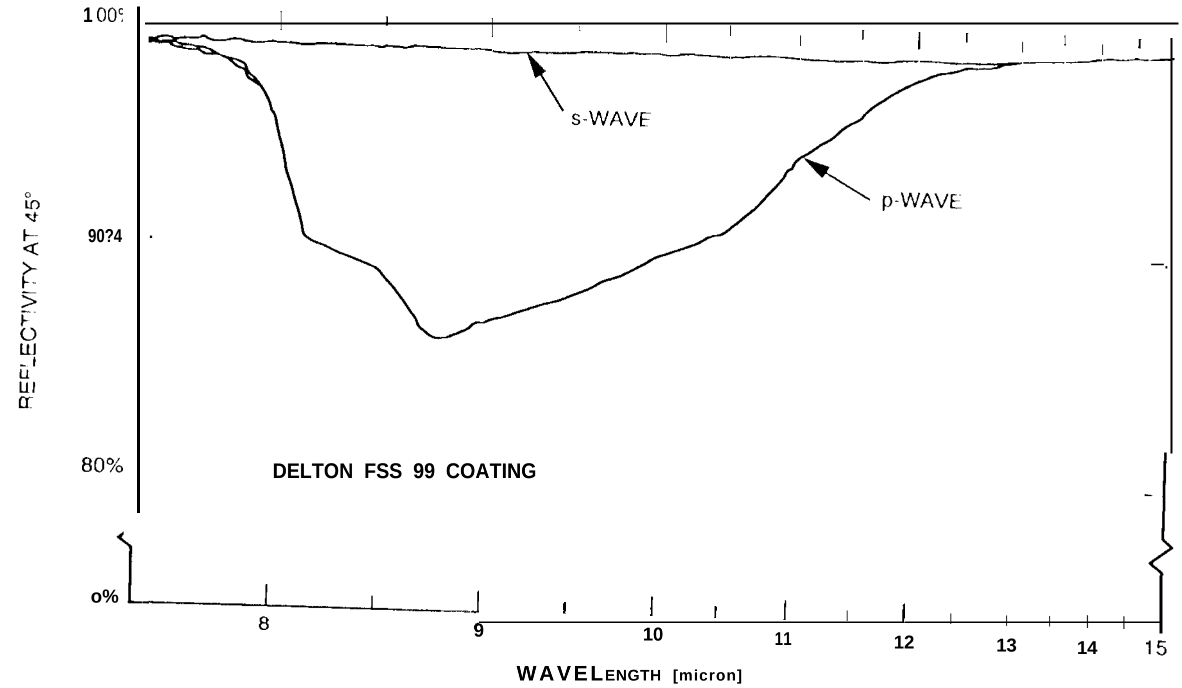

Figure 5. The spectral reflectivity for s- and p-wave between 7.5 and 15.5 μm (shown relative to the reflectivity of pure gold) introduces a scan angle dependent polarization effect with a peak-to-~k modulation of about four NEN units at 9μm. The first order correction based on pre-launch characterization reduces the polarization effect to less than onc NEN unit.

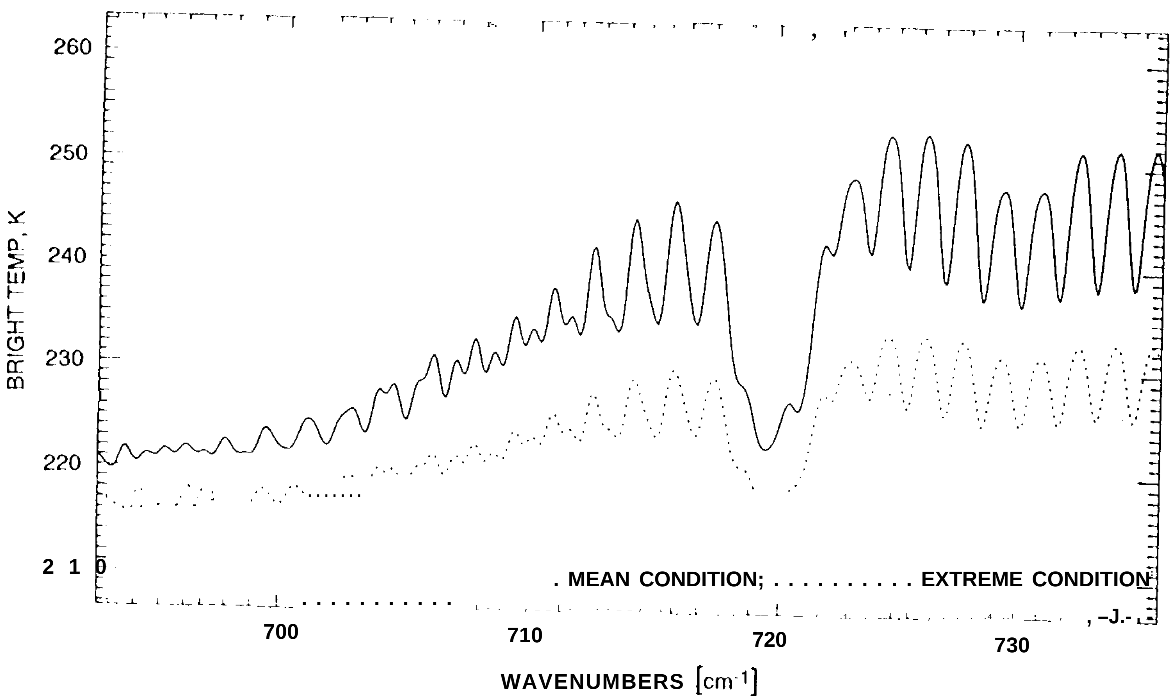

Figure 6, The upwelling radiance spectrum in the 720-740 cm-l region of the spectrum, shown here for the average and extreme winter/mid-latt itude climatology, illustrates the approach taken for the absolute spectral calibration of AIRS.

Depending on a spectral calibration which requires knowledge of the vertical temperature and moisture structure seems like a circular argument, given that AIRS is expected to measure temperature and moisture profiles. Fortunately, a rough approximation of the temperature structure suffices to accomplish the spectral calibration. In most regions of the *3.7 -.15.4* μm spectrum, particularly near the edges of atmospheric window regions, the calculated spectrum based on the temperature and moisture profiles expected from climatology can be substituted for the tnrc upwelling radiance spectrum. This is illustrated in Figure 6. The globe can be subdivided into rough climate zones: Midlatitude/tropical, summer/winter, ocean/land. Each climate zone can be represented by a mean vertical profile and an extreme hot/cold/dry/wet profile. The climatology set with the largest difference between the mean and the extreme profile is the midlatitude/ winter/ ocean set. Figure 6 shows the spectral radiance calculated for mean and the extreme condition in the observed spectrum for the 693-736 cm^{-1} (13 .59 -14.39 pm) region of the spectrum. This is part of the coverage of focal plane module M-11 shown in Figure 3. Now consider the 726-736 cm^{-1} region, which is at the edge of the C02 band. While the brightness temperature difference between the precalculated mean and the "observed" extreme case is about 20K, the maxima and minima of the spectra arc precisely aligned. This is because wc picked a region with weak lines, not contaminated with underlying water lines, and the AIRS spectral resolution is adequate to resolve the individual lines. A climatology based guess of the temperature profile is thus adequate for spectral calibration.

The AIRS ground data processing system uses the AMSU and MHS to obtain a "microwave only" first guess of the temperature and moisture profiles. This first guess, which is always more accurate than climatology, could be used for spectral calibration accuracy monitoring and/or for spectral calibration. At this point it appears to be computationally more convenient to precalculate and store spectra for eight climatology conditions than to calculate the upwelling spectra each time from the microwave first guess.

Uncertainty in the temperature or moisture profile is thus not an issue for wavelength calibration if this region is used. Although not all spectral regions covered by AIRS can be used for spectral calibration with as much case as the 726-736 cm-1 example, there arc enough regions to accomplish the least-square solution for the four kcy grating equation parameters discussed above. Finite signal to noise is the actual limit to the achievable spectral calibration accuracy. We indicated previously that wc expect almost the entire change in the spectral calibration after the initial stabilization period to due to a change AXO in Xo, a shift of the entire in the direction of dispersion. This produces a shift $\Delta\lambda = -d/m * \Delta Xo/L$ in the wavelength calibration. We use the 726-736cm^{-1} region of the AIRS spectrum to illustrate that, with AIRS nominal NEAT, $\Delta\lambda$ can be determined to satisfy the required spectral calibration accuracy with only four spectra. For conditions similar to those encounter in the 726-736 cm^{-1} region discussed above, the spectral calibration accuracy, AL, is related to the spectral resolution width, $\Delta\lambda$, the peak-peak contrast in the signal, C, and the rms noise, NEAT, of each detector element and the number of detector elements, N, in the array through

$$AL= 2* NEAT* \Delta\lambda / C * sqrt(2/N).$$

For the 726-736 cm-l region wc have C=1 2K, NEAT=0.35K, N=1 8, resulting in $\Delta L=0.02*\Delta\lambda$. This accuracy is fully adequate for the rout inc monitoring the calibration. Achieving the required wavelength calibration accuracy of 0.01 $*\Delta\lambda$ requires in principle only four observation of the upwelling radiance. In practice, hundreds of upwelling spectra arc available to monitor the accuracy of the spectral calibration and to apply corrections to the calibration, if necessary.

7. SUMMARY

The Al RS inst rument represents a major advance in passive IR remote sensing technology. The AIRS spectral and radiometric calibration effort insures that the ncw data about the atmosphere, land and oceans for application to climate studies and weather prediction will also be of unprecedented accuracy. AIRS, AMSU and MHS constitute an advanced atmospheric sounding system designed to meet the operational weather prediction requirements of NOAA and the global change research objectives of NASA. The validation of the combined capability of the three inst ruments on the EOS-PM spacecraft will start in the year 2000. A light-weighted derivative of the AI RS/AMSU/MHS system is a strong candidate for operational deployment as part of the converged U. S. Meteorological System, NPOESS, starting in the year 2005.

8. ACKNOWLEDGMENTS

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